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After the fall: did coffee plants in Puerto Rico survive the 2017 hurricanes?

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ABSTRACT

Hurricanes Irma and Maria hit Puerto Rico in September 2017. According to initial estimates, 90% of coffee plants were destroyed. We surveyed damage to coffee plants in 81 plots throughout the coffee-growing area of west-central Puerto Rico; we used the change in the Landsat derived Normalized Difference Vegetation Index (NDVI) to estimate damage to vegetation in coffee farms. ΔNDVI values ranged from 0 to 0.36; almost half of all plots had ΔNDVI ≤ 0.17 and had less than 20% damaged plants, whereas twelve plots in six municipalities were severely hit and had ≥80% plants damaged. Damage varied greatly among plots and even within plots. Probability of damage was significantly higher in sites with north- and south-facing slopes than in sites with east- and west-facing slopes. Neither minimum distance from the center of Hurricane Maria, altitude, precipitation and maximum wind speeds were related to extent of damage. Coffee berry borer (*Hypothenemus hampei*) populations decreased after the hurricanes but recovered quickly. Understanding patterns of damage and their causes may help suggest ways to protect the coffee industry from future natural disasters.

1. Introduction

Hurricane Irma (Category 5) grazed Puerto Rico on September 6, 2017. It was closely followed by a direct hit from Hurricane Maria (Category 4) on September 20th. Damage to Puerto Rican agriculture was estimated at $45 million and $780 million, respectively (Robles and Ferré-Sadurní, 2017). Many news reports focused on damage to coffee and coffee farms.

Coffee is the principal crop of the mountainous area of west-central Puerto Rico. The region is geographically and geologically diverse (Muñiz and Monroig, 1994; Fain et al., 2018). The crop has great economic, social and cultural importance in a region with many socioeconomic challenges. Harvesting had started in some areas before Irma and Maria, but most of the 2017 coffee crop was lost.

The quantification of damage to coffee (and other crops) is mostly anecdotal. Preliminary estimates from three municipalities (Jayuya, Yauco and Ponce) all stated that 90% of coffee plants were destroyed (Hoffman, 2017; Kennedy, 2017; Newton and Quiñones-García, 2017). (Here we focus exclusively on damage to plants; we do not consider loss of coffee fruits or the coffee crop.) However, no data have been published on the extent of damage, how it varied across the coffee-growing region, or what environmental variables could explain this variation.

The principal pest of coffee is the coffee berry borer (CBB), an invasive beetle that arrived in Puerto Rico in 2007 (NAPPO, 2007). In Puerto Rico CBB infestation tends to be severe relative to other countries (Mariño et al., 2017). Several coffee growers have told us that the only positive aspect of the hurricanes is that the CBB was carried off by the wind or destroyed along with the crop, but no data are available to evaluate this claim.

In this study we asked the following questions:

1) What proportion of coffee plants were knocked down or defoliated by the hurricanes? We predicted that damage would match the levels estimated in news reports, 90%.
2) Did damage vary with proximity to Hurricane Maria's track? We predicted more damage in Ciales and Orocovis, at the NE edge of the coffee country, since they were closest to the center of Maria, (Fig. 1; wind velocity is inversely proportional to distance from the eye), and less damage in Yauco and Maricao, which were further away.
3) Did damage to coffee plants vary with peak wind speed, altitude and orientation of the plot? Did it reflect changes in vegetation in-

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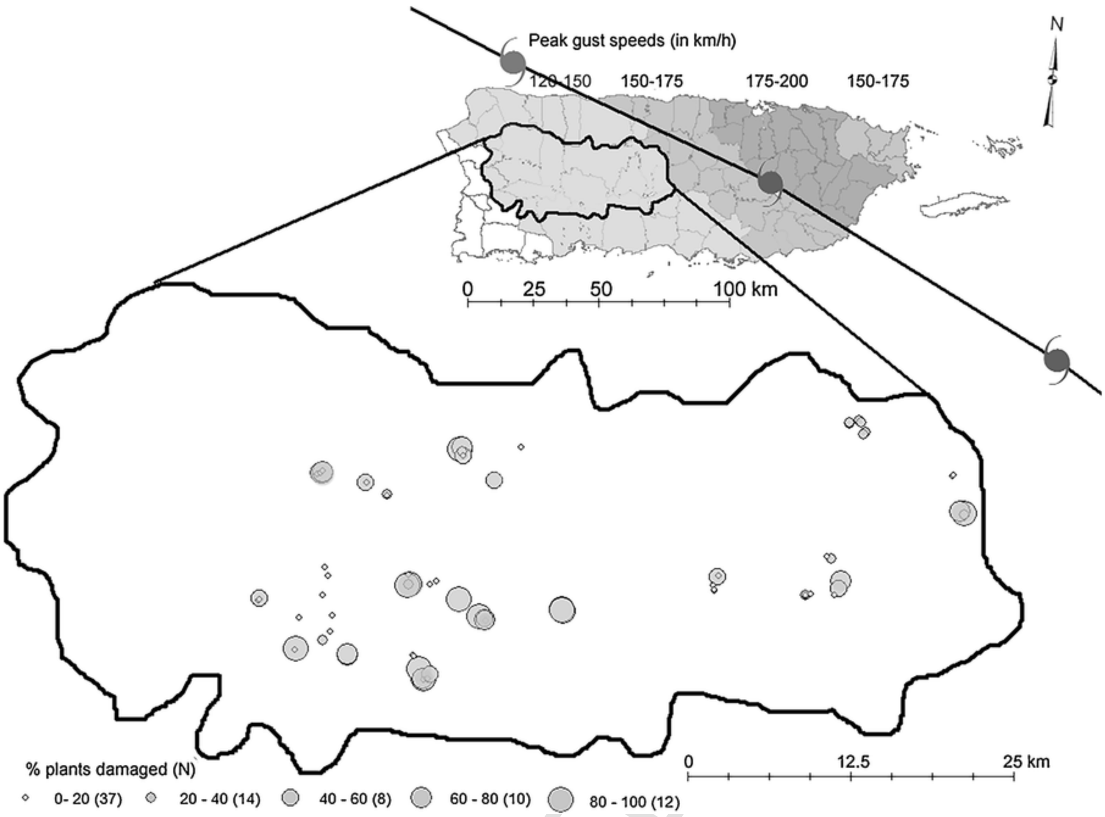

Fig. 1. Map of Puerto Rico showing the paths of Hurricane María, wind speed zones, and coffee farms sampled in this study (inset).The outline represents the main coffee-growing area. Size of circles indicates levels of damage on each plot. Wind speed data from Pacific Disaster Center (2017). The path of Hurricane Irma is shown off the northeast corner of Puerto Rico.

dices (ΔNDVI, Hu and Smith, 2018)? We predicted that higher peak wind speed would be associated with higher incidence of damage to coffee plants. Similarly, plants at higher altitudes would be exposed to higher wind speeds, and therefore sustain more damage. Also, we predicted that plants on north-facing slopes would be more exposed to strong winds and therefore receive more damage, since Maria passed to the north and the rotation of the storm was counterclockwise.

4) Did damage to coffee plants correlate with number of CBBs found in remaining fruits? We predicted a positive relationship, because when most plants and fruits are knocked down, the CBB will concentrate in the few remaining fruits, so population per fruit should increase.

2. Methods

2.1. Sites and census

We surveyed a total of 81 plots on 45 farms in nine municipalities in the coffee-growing region of west-central Puerto Rico (Fig. 1). Plots were defined as areas with ~100 *Coffea arabica* plants. The plots were selected based on previous studies and on accessibility, because many areas were still unreachable when the survey was conducted. The order and timing of survey visits was determined by when roads to each area became accessible. When more than one plot was sampled per farm, the plots differed in altitude, spatial orientation, exposure or environment (e.g., sun vs. shade). Plots were visited between October (one month after Hurricane Maria) and December 2017. Data for each site are shown in Table S1.

In each plot we surveyed ~100 coffee plants (N = 58–187 plants/plot, x = 104) large and old enough to bear fruit. Each plant was assigned to one of three categories: **healthy**, if the plant was alive, erect and more or less intact; **defoliated**, if the plant was erect but entirely or almost entirely without leaves, or **fallen**, if the plant was knocked down at an angle of $<45^\circ$ from the ground (Fig. 2). Some defoliated and fallen plants were dead; some were alive but with little chance of recovery (see Discussion). The number of **damaged** plants was defined as the sum of defoliated and fallen, for reasons explained below.

Coordinates and altitude were taken for each plot with a handheld GPS device; orientation was determined using Google Earth (and corroborated in the field as well). Closest distance to the path of Hurricane Maria was based on the best track line reported by the National Oceanic Atmospheric Administration (NOAA)(https://www.nhc.noaa.gov/gis/archive_besttrack_results.php?id = al15&year = 2017&name = Hurricane%20MARIA). Precipitation data were taken from a map of estimated rainfall published by the National Weather Service managed by NOAA (https://www.weather.gov/sju/maria2017). Estimated peak wind gust speeds were taken from the Space Science and Engineering Center (SSCE) and Cooperative Institute for Meteorological Satellite Studies (CIMSS) (http://www.ssec.wisc.edu/through-the-atmos/ttaspring2018/TtA_Winter_Spring_2018.pdf).

2.2. Normalized difference vegetation index (NDVI)

We used change in the Normalized Difference Vegetation Index (NDVI) to estimate damage to vegetation in coffee farms. Higher ΔNDVIs imply more damage to vegetation by the hurricane (Hu and Smith, 2018). To calculate NDVI we extracted the Landsat 8 bands 4 (red) and 5 (NIR) for each of our coffee plots from pre-Maria and post-Maria false-color images made by Feng et al. (2018). NDVIs vary depending on radiation absorption by chlorophyll in the red spectral and reflectance in the near infrared region (Bălulescu et al., 2013); they were used by Hu and Smith (2018) to indicate loss of vegetation in forests from Puerto Rico and Dominica due to Hurricane Maria. We deter-

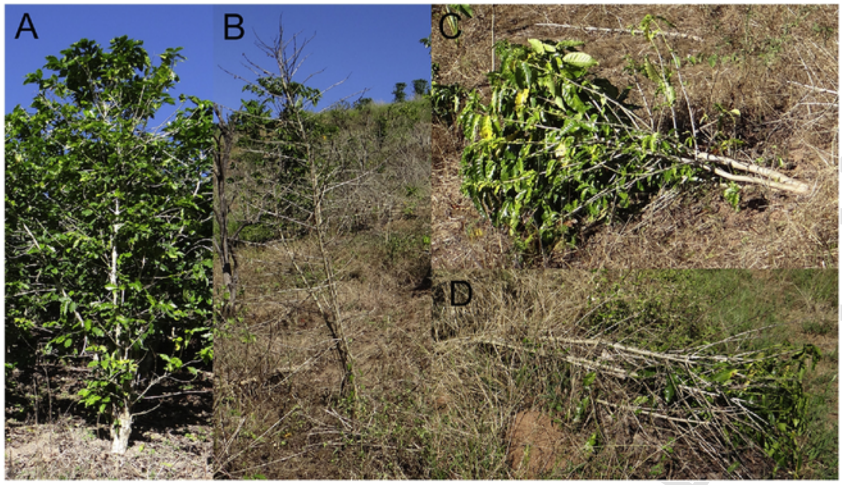

Fig. 2. Examples of **healthy** (A), **defoliated** (B), and **fallen** (C, D) coffee plants, the categories used in this study.

mined ΔNDVI by subtracting the pre-hurricane NDVI values from post-hurricane NDVI values.

2.3. CBB

To assess CBB populations in coffee fruits, we collected ~50 CBB-bored fruits from each plot. (In some plots fewer fruits were available because they had been harvested previously or pruned by the hurricanes.) In the lab, bored fruits were dissected and the number of adults, eggs and larvae counted as described previously (Mariño et al., 2016, 2017); mortality of adult females also was determined. It was not possible to estimate incidence of infestation by CBB because not enough fruits were present in many sites. Populations pre- and post-hurricane were compared for four sites each in Adjuntas and Utuado (the only sites for which pre-hurricane data were available, collected every two weeks from June-September 2017).

2.4. Statistical analysis

We used generalized linear mixed models (GLMM) to test the effect of orientation, altitude, distance from the path of the hurricane, estimated precipitation and estimated peak wind speed on damage to coffee plants. These environmental variables were considered as fixed factors. A binomial error distribution was used for the variable healthy vs. damaged coffee plants. A GLMM with a Poisson errors distribution was used to compare the CBB populations per fruit before and after the hurricanes. For all models site and municipality were considered as random variables.

Interval classes for altitude, distance from the hurricane path, peak wind gust speeds and precipitation were defined using the Jenks natural breaks classification, which reduces the variance within classes and maximizes the variance between classes (Jenks, 1967). Altitude was divided into six classes (327–385, 385–469, 469–542, 542–622, 622–712 and 712–894 m asl). Distance was separated into five classes (9.4–12.7, 12.7–25.3, 25.3–31.3, 31.3–35.9 and 35.9–41.9 km). Precipitation data were divided into five classes (< 6.91, 6.91–12.15, 12.15–14.78, 14.78–18.38 and 18.38–22.95 mm). Maximum peak wind speeds were divided into five classes (< 117,class 2: 117–123, 123–128, 128–135 and 135–142 mph). Orientation was categorized as the four cardinal directions (N, S, E, W).

Spearman’s rank correlations were used to determine the relationship between ΔNDVI and proportion of damaged and fallen plants. Also, we determined the relationships between proportion of damaged plants and ΔNDVI with altitude, closest distance from the path of the center of Maria, precipitation, wind peak gusts, total number of individuals per fruit and proportion of mortality of CBB adult females. Spearman's was chosen because data did not have normal distributions or homogeneity of variance even when transformed (Zar, 1998). All data analyses were performed in R (R Core Team, 2017) and GLMM models were fitted using the R package lme4 (Bates et al., 2014)

3. Results

3.1. Survival of coffee plants

Overall, 64% of coffee plants were categorized as healthy, 16% defoliated, and 20% fallen (Graphical Abstract) from a total of 8431 plants surveyed. However, damage varied greatly among sites and plots (Table S1). Eleven plots in six municipalities had ≥99% healthy plants, whereas four plots in Adjuntas and Yauco had 0% healthy plants. Almost half of all plots had ≤20% of plants damaged (that is, defoliated + fallen), whereas twelve plots in six municipalities were severely hit and had ≥80% plants damaged (Fig. 3a).

Generalized Linear Mixed Models showed that the estimated probability of damage was significantly higher in sites with north- and south-facing slopes then in sites with east- and west-facing slopes (GLMM, binomial errors, north Z = 1.76, $p = 0.017$; south Z = 1.70, $p = 0.024$) (Fig. 4b, Table 1). The effect of the other four variables on damage to plants did not differ significantly among classes (Table 1). Also, the relationships between damage and altitude, distance, maximum peak wind speed and precipitation were not significant (altitude: rho = 0.04, $p = 0.71$; distance: rho = 0.08, $p = 0.47$; wind peak gusts: rho = -0.07, $p = 0.51$ and precipitation: rho = 0.001, $p = 0.98$) (Table 2).

ΔNDVI values ranged from 0 to 0.36; almost half of all plots had ΔNDVI

≤ 0.17. These results are similar to observations of coffee plants in situ, in which almost half of plots had less than 20% damaged plants (Fig. 3a and 3b). ΔNDVI values were positively correlated with proportion of damaged plants (rho = 0.47, $p < 0.0001$) and proportion of fallen plants (rho = 0.42, $p = 0.0005$). But relationships between ΔNDVI and environmental variables were not significant (altitude: rho = -0.028, $p = 0.82$; distance: rho = -0.20, $p = 0.11$; wind peak gusts: rho = 0.18, $p = 0.15$ and precipitation: rho = 0.038, $p = 0.761$) (Table 2).

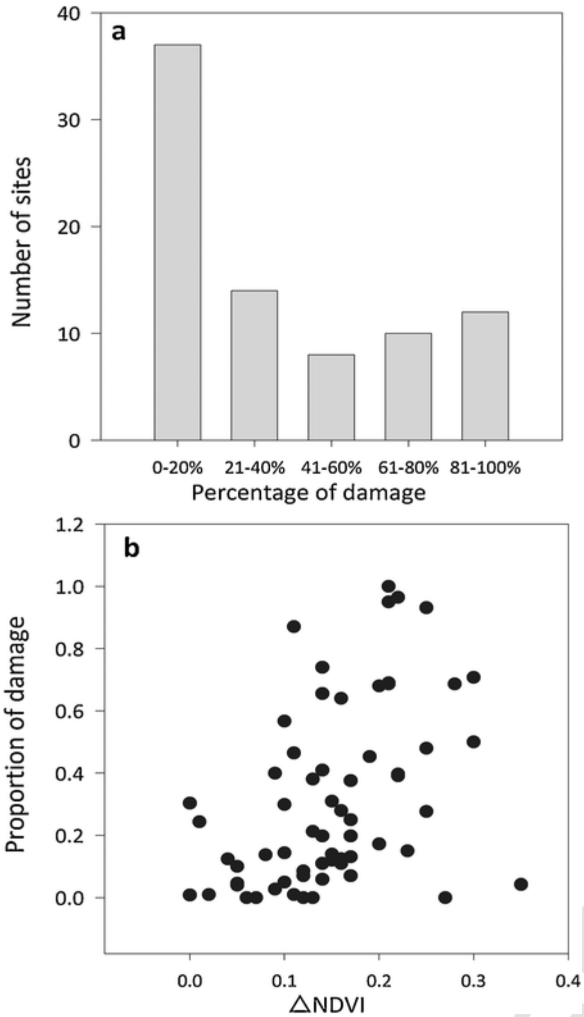

Fig. 3. Distribution of variation in damage to coffee plants among the 81 sites sampled in situ and Landsat derived ΔNDVI (a) % damaged plants = % defoliated + % fallen (b) relationship between proportion of damage vs. change in the normalized difference in vegetation index (ΔNDVI) (Spearman's correlations coefficients: rho = 0.47, $p < 0.0001$).

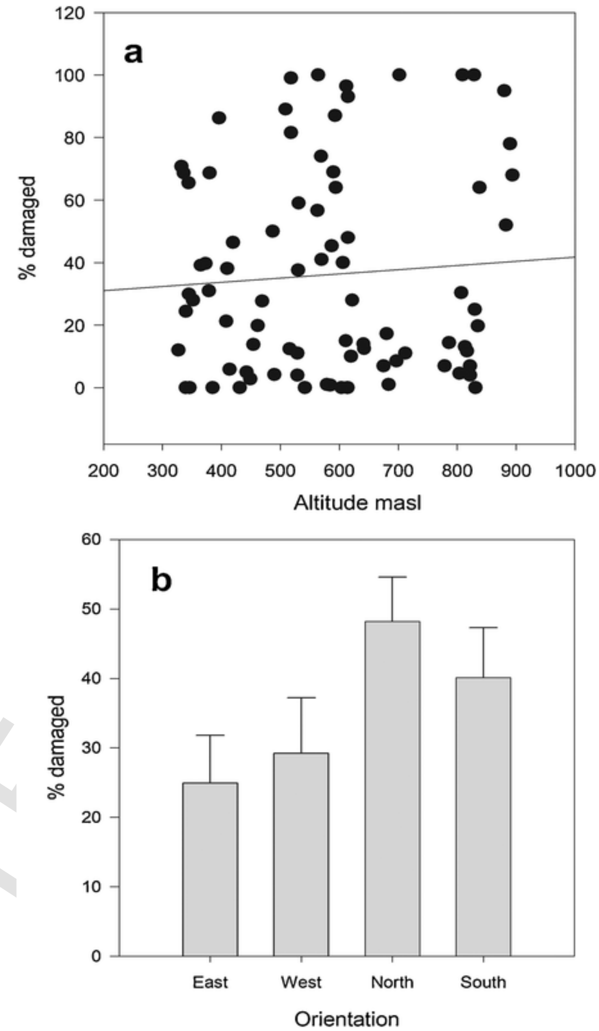

Fig. 4. Variation in damage to coffee plants according to altitude (a) and orientation (b) of sites. % damaged plants = % defoliated + % fallen. Error bars show +1 s. e.

3.2. CBB damage

In Utuado and Adjuntas the number of CBB individuals per infested fruit declined sharply and significantly following Hurricane Irma (Fig. 5, Table 3). However, a month after Maria, CBB populations had increased to approximately their previous levels. (There was no opportunity to sample between Irma and Maria, or in the first three weeks after Maria.) This pattern suggests that the CBB was negatively affected by the hurricanes but recovered quickly.

Number of individuals of CBB per fruit and proportion of dead adult females was not significantly related to damage to the plants in the plot (rho = -0.06, p = 0.61 and rho = -0.16, p = 0.206, respectively) (Table 2), contradicting the hypothesis.

4. Discussion

4.1. Extent of damage to coffee plants

Damage to coffee from Irma and Maria was severe, but not as severe as initially reported. Three news reports from different municipalities estimated that 90% of plants were destroyed (Hoffman, 2017; Kennedy, 2017; Newton and Quiñones-García, 2017); we found that level of damage in only 10% of plots sampled. In contrast, almost half of the plots sampled had less than 20% of plants damaged and ΔNDVI < 0.17 (Fig. 3a and b).

We considered damaged plants as those knocked down plus those that were defoliated. It is possible that some of the defoliated plants will be able to recover. Some growers told us that they were planning to prune defoliated plants to the crown to give them a chance to regenerate (in which case they would take two years to fruit again). However, others told us that these plants were lost to *piloneo*, an excessive shaking which causes damage to the roots from which few if any coffee plants can recover (Gómez, 2017). There is very little information in the literature on this condition (nor is it mentioned in the recent *Compendium of Coffee Diseases and Pests* (Gaitán et al., 2015), so it is hard to reconcile these conflicting assessments or predict how many of the defoliated plants could be saved. Shaking as a cause of mortality has been documented in some forest trees (Lugo, 2008).

4.2. Spatial variation in damage and its relation to environmental factors

Neither minimum distance from the center of Hurricane Maria nor altitude, precipitation or maximum wind gust speed were related to extent of damage, as measured in situ as % damaged plants and from satellite images as vegetation index (ΔNDVI). Data for precipitation

Table 1
GLMM estimates for coffee plant damage after Hurricane Maria as explained by spatial orientation, altitude, distance from the past of the hurricane, precipitation and maximum wind gust speed.

Model Variable			
Orientation	**Estimate**	**Z value**	***p***
East vs. North	1.7695	2.376	0.017*
East vs. South	1.7016	2.251	0.024*
East vs. West	0.6146	0.699	0.559
Altitude[a]	**Estimate**	**Z value**	***p***
Class 1 vs. Class 2	−0.4808	−0.450	0.133
Class 1 vs. Class 3	0.6660	0.578	0.563
Class 1 vs. Class 4	0.9163	0.882	0.378
Class 1 vs. Class 5	0.3841	0.301	0.763
Class 1 vs. Class 6	0.5851	0.482	0.630
Distance from the path hurricane[b]	**Estimate**	**Z value**	***P***
Class 1 vs. Class 2	−0.9419	−0.693	0.488
Class 1 vs. Class 3	0.7136	0.492	0.623
Class 1 vs. Class 4	0.7885	0.549	0.583
Class 1 vs. Class 5	−0.2440	−0.177	0.860
Precipitation[c]	**Estimate**	**Z value**	***P***
Class 1 vs. Class 2	−0.4347	−0.293	0.770
Class 1 vs. Class 3	- 1.8733	−0.827	0.408
Class 1 vs. Class 4	0.3044	0.183	0.855
Class 1 vs. Class 5	−1.4630	−0.674	0.501
Maximum peak wind speed[d]	**Estimate**	**Z value**	***P***
Class 1 vs. Class 2	−0.5130	−0.346	0.729
Class 1 vs. Class 3	1.5102	1.392	0.164
Class 1 vs. Class 4	−0.2223	- 0.193	0.847
Class 1 vs. Class 5	−0.8246	−0.773	0.440

[a]Altitude was divided into six classes (327–385, 385–469, 469–542, 542–622, 622–712 and 712–894 m asl). [b]Distance was separated into five classes (9.4–12.7, 12.7–25.3, 25.3–31.3, 31.3–35.9 and 35.9–41.9 km). [c] Precipitation data were divided into five classes (< 6.91, 6.91–12.15, 12.15–14.78, 14.78–18.38 and 18.38–22.95 mm).[d] Maximum peak wind speeds were divided into five classes (< 117,class 2: 117–123, 123–128, 128–135 and 135–142 mph). General linear mixed models: *** = $p < 0.001$, ** = $p < 0.01$, * = $p < 0.05$, · = $p < 0.1$.

Table 2
Spearman's rank correlations between proportion of damage to coffee plants and ΔNDVI (normalized difference vegetation index) with, altitude, distance from the past of the hurricane, precipitation and maximum wind gust speed, number of individuals of the coffee berry borer (CBB) *Hypothenemus hampei* per bored fruit and proportion of mortality of CBB adult females.

Variables		Spearman (rho)	*p* –value
Proportion of damage plants	Altitude	0.004	0.717
	Distance from the path hurricane	0.141	0.210
	Precipitation	0.001	0.986
	Wind speed gusts	- 0.072	0.519
	Number of individuals of CBB per fruit	- 0.065	0.610
	Mortality of CBB adult females	- 0.161	0.206
Δ NDVI	Proportion of damage plants	0.471	< 0.001
	Proportion of fallen plants	0.423	0.0005
	Altitude	- 0.028	0.820
	Distance from the path hurricane	- 0.202	0.113
	Precipitation	0.038	0.761
	Wind speed gusts	0.184	0.154

and wind gust speeds are estimates; precise measures are not available, since the wind measurement devices in Puerto Rico were destroyed by the storm (http://www.weather.gov/sju/maria2017); (Meyer, 2017; Schmidt et al., 2017). Furthermore, the available data do not have spatial resolution sufficient for the needs of this study. For example, for available wind gust speed data a single pixel covers several sites, which in some cases had very different levels of damage.

In this study, adjacent plots often had dramatically different outcomes. For example, two sites (S67 and S69) sampled on the same farm, at the same altitude and distance from the hurricane center, and with the same precipitation and (presumably) wind gust peaks, had very different levels of damage: 0% and 66%, respectively (Table S1). Variation at an even smaller spatial scale was observed in a plot in Lares, where rows of healthy plants alternated with rows of fallen plants (Fig. S1).

It is difficult to explain such fine-scale variation in damage. The extreme variation observed over a small spatial scale may reflect differences in topography, exposure and soils, as well as localized differences in wind speed and direction. Coffee varieties, plant age and height, pruning, root system vigor and surrounding vegetation may have influenced outcomes and may be decisive in the recovery of the crop (see Lugo, 2008).

This pattern of fine-scale variation suggests that decisions about replanting and cultural practices should be made on a plot-by-plot basis and not generalized to municipality or geographic area.

ΔNDVI (based on satellite images from Landsat 8 and Sentinel 2) was used to estimate the damage caused by Hurricane Maria to forests in Puerto Rico (Hu and Smith, 2018). Contrary to the present study, they found a negative relationship between ΔNDVI and distance from the center of Maria and a positive relationship between ΔNDVI and altitude. However, Hu and Smith's study sampled all of Puerto Rico, whereas ours was limited to relatively few points in a much smaller area.

There was a positive, significant relationship between % damaged coffee plants and ΔNDVI, but it did not explain much of the variation. Our study only considered coffee plants, whereas ΔNDVI reflects all the vegetation present in an area. Some fallen coffee plants still had leaves, in which case ΔNDVI would not be an accurate predictor of damage. And most of the plots sampled were sun coffee, which had low NDVIs even before the hurricane. For example, sites S67 and S69 were similar in ΔNDVI (0.13 and 0.14, respectively), despite differences in outcomes mentioned above.

4.3. Survival of the coffee berry borer (CBB)

Various coffee-growers told us that the hurricanes carried off the coffee berry borer (usually expressed as "*María se llevó la broca*"). This is not true: CBB populations per infested fruit declined after Hurricane Irma but recovered rapidly. CBB reproduction may have slowed or stopped during the hurricanes and resumed once conditions stabilized. There are fewer CBBs at present because fewer fruits are available; most fruits were harvested or destroyed. In the aftermath of Maria some coffee farms will be neglected or abandoned, and unharvested or feral coffee is a reservoir of CBB between crops (Aristizábal et al., 2017). These factors suggest that as the coffee crop is reestablished in the next few years, the CBB will reach its former levels of infestation and damage. Hurricane damage make some forest trees more susceptible to attack by beetles (Lugo, 2008).

4.4. Damage to coffee plants in context

Of course, direct damage to coffee plants themselves is only part of impact on agriculture. Infrastructure such as roads, power and processing equipment was even more seriously damaged than the coffee plants

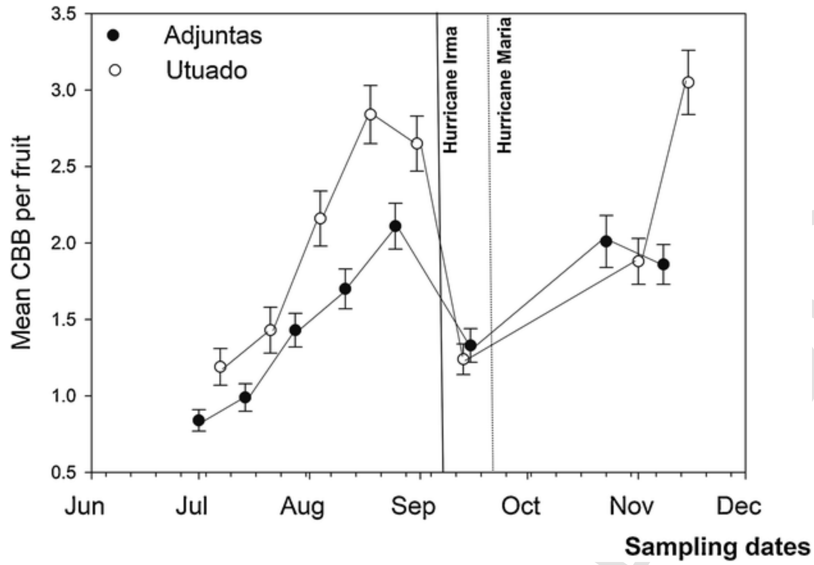

Fig. 5. Populations of the coffee berry borer (CBB) per infested fruit before and after Hurricane Irma and Hurricane María in September 2017. Error bars show ±1 s. e.

Table 3
GLMM estimates for total number of coffee berry borer (*Hypothenemus hampei*) individuals per fruit before and after Hurricanes Irma and Maria.

Model Variable			
CBB per fruit			
Between vs. Pre-hurricane	0.6170	15.91	< 0.001***
Between vs. Post-hurricane	0.4324	10.17	< 0.001***

General linear mixed models: *** = $p < 0.001$, ** = $p < 0.01$, * = $p < 0.05$, · = $p < 0.1$.

themselves, according to Carlos Flores Ortega, Puerto Rico's Secretary of Agriculture (and a coffee grower himself) (Figueroa Cancel, 2017). Some parts of the coffee-growing area received 50–65 cm of rain during Hurricane Maria (http://www.weather.gov/sju/maria2017) causing water and soil run-off, severe erosion and landslides, which also damaged coffee plants. And damage to shade trees caused by both hurricanes left many plants vulnerable to sunscald. Shade trees help buffer hurricane impacts on coffee farms (Lin et al., 2015) so their loss will increase susceptibility to future storms (Everham and Brokaw, 1996). In this and other respects, there may be long-term effects that cannot yet be measured (Lugo, 2008).

Likewise, we did not estimate damage to the 2017-18 coffee crop. In some areas at lower elevations harvesting was nearly completed before the hurricanes, but about 90% of the crop was lost. Coffee harvests in Puerto Rico have declined over the last two decades. The 2017-18 crop was originally expected to reverse this trend, but now the crop is expected to be a record low.

Coffee production in the Caribbean, Central America and Mexico is frequently affected by hurricanes and tropical storms. Recent examples include Hurricanes Mitch (1998, Mexico and Central America), Ivan (2004, Jamaica), Stan (2005, Mexico and Central America), Gustav (2008, Caribbean), Sandy (2012, Caribbean) and Otto (2016, Central America). However, none of these storms caused as much damage to coffee as Hurricane Maria in Puerto Rico. In most cases preliminary estimates of damage were published in news stories, but they usually referred to percent loss of the coffee harvest rather than damage to plants. None of these reports presented data or described sampling methodology; the present study is apparently the first to do so.

Information about how and why damage varied among sites is useful for making decisions about replanting. An estimated 6–8 million coffee seedlings will be available in Puerto Rico, but this will only supply part of the plants that were lost (CyberNews, 2017). Since hurricanes are likely to be more powerful in the future because of climate change, understanding patterns of damage may help decide how to plant the available seedlings most effectively. More precise data about variation in wind speed and dissipation would have been useful in this context, but these data are not available for Hurricane Maria. Wind energy increases as the cube of velocity, so small differences in wind speed can cause large differences in kinetic energy (Lugo, 2008). It is hard to understand why more robust wind speed measurement devices were not in use in an area that sees so many hurricanes.

Conflict of Interest

The authors declare no conflict of interest.

Acknowledgments

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.agee.2018.07.011.

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